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The Effect of Transverse Curvature On the Fluctuating Wall Pressure and Structure Of Boundary Layer Turbulence

**A Paper Presented at the ONR State-of-the-Art
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**Naval Undersea Warfare Center Detachment
New London, Connecticut**

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PREFACE

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REVIEWED AND APPROVED: 19 AUGUST 1993

A handwritten signature in dark ink, reading "F. J. Kingsbury". The signature is written in a cursive style with a large, stylized "K".

**F. J. Kingsbury
Head, Submarine Sonar Department**

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13. ABSTRACT (Maximum 200 words) This document consists of the text and viewgraphs of a paper presented at the ONR Workshop on Nonequilibrium Turbulence held at Arizona State University in Tempe, Arizona, from 10-12 March 1993. This workshop was the first step of an ONR Accelerated Research Initiative (ARI) to establish the state-of-the-art for theory, computation, and experimentation relevant to turbulence in a nonequilibrium state, or, more generally, to turbulence in complex flows. The overall goal of the initiative is to understand the behavior of turbulence in such complex conditions in order to advance our prediction and control capabilities. When a cylinder in axial flow is sufficiently long and thin, the growth of the boundary layer results in its thickness exceeding the radius of the cylinder such that the three-dimensional effects due to transverse curvature cannot be neglected. With this condition, the wall of the cylinder provides less constraint on the outer flow and motion of eddies than is experienced in an equilibrium flat plate boundary layer, introducing an avenue for enhanced inner-layer/outer-layer interaction and modified turbulence activity. In this paper, we present results of measurements of the fluctuating wall pressure and turbulent streamwise velocity in the turbulent boundary layer on a cylinder in axial flow to identify the coherent structures that contribute to the fluctuating pressure at the wall. Determining the influence of transverse curvature on the relationship between the wall pressure and velocity field allows examination of its effect on the structure of equilibrium boundary layer turbulence.				
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THE EFFECT OF TRANSVERSE CURVATURE ON THE FLUCTUATING WALL PRESSURE AND STRUCTURE OF BOUNDARY LAYER TURBULENCE

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Viewgraph 1

This paper presents recent results on the effect of transverse wall curvature on the fluctuating wall pressure and the structure of boundary layer turbulence. The experiments were performed at Northwestern University in collaboration with Richard Lueptow, Professor of Mechanical Engineering, with the support of the Towed Array Exploratory Development Branch (Code 2141) at the Naval Undersea Warfare Center (NUWC) under the sponsorship of the Office of Naval Research (ONR).

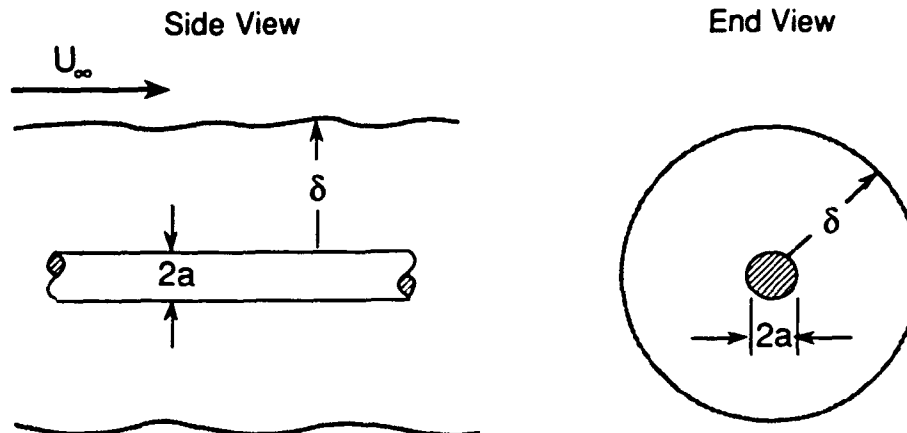
STATEMENT OF THE PROBLEM

- **INVESTIGATION:** Examine relationship between fluctuating wall pressure and turbulent flow structures in a boundary layer with transverse wall curvature
 - **APPROACH:** Perform simultaneous measurements of fluctuating wall pressure and fluctuating streamwise velocity in a TBL on a cylinder in axial flow
 - **OBJECTIVE:** Understand how transverse curvature influences fluctuating wall pressure and turbulence structure that exists in an equilibrium flat plate boundary layer
-

Viewgraph 2

This investigation examines the relationship between the fluctuating wall pressure and turbulent flow structures in a boundary layer with transverse wall curvature. The approach taken has been to perform simultaneous measurements of the fluctuating wall pressure and fluctuating streamwise velocity in a turbulent boundary layer (TBL) on a cylinder in axial flow. The objective is to better understand how transverse curvature influences the fluctuating wall pressure and turbulence structure that exist in an equilibrium flat plate boundary layer.

THE TURBULENT BOUNDARY LAYER ON A CYLINDER IN AXIAL FLOW



$\delta/a = 0$: Flat Plate Boundary Layer (Limiting Case)

$\delta/a = 5.04$: Present Investigation

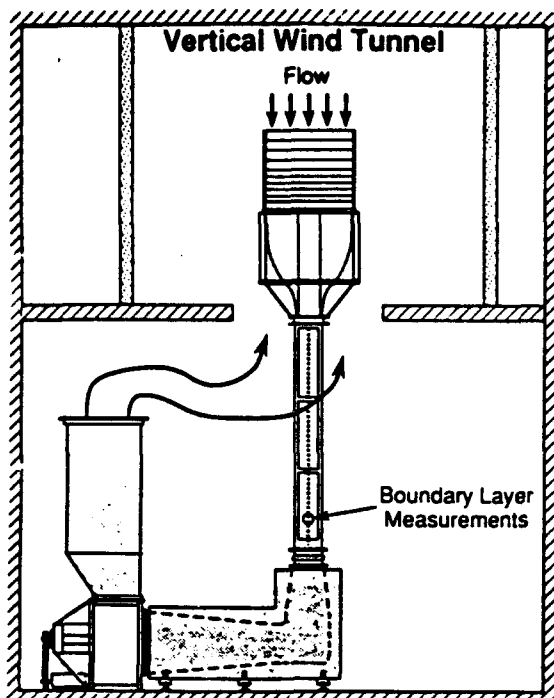
- 3-D Effects Due to Transverse Curvature Alter Mean Flow
- Outer Flow Independent of Wall

$\delta/a \rightarrow \infty$: Cylindrical Wake Flow (Limiting Case)

Viewgraph 3

This viewgraph illustrates the overall character of a turbulent boundary layer on a cylinder in axial flow. The transverse curvature of the cylindrical boundary layer is characterized in terms of the ratio of δ (boundary layer thickness) to a (cylinder radius). A δ -to- a ratio of zero is the limiting case of a flat plate boundary layer (i.e., $a \rightarrow \infty$), while a δ -to- a ratio approaching infinity is the limiting case of a cylindrical wake flow (i.e., $a = 0$). For the present measurements, δ/a was equal to 5.04, as the sketch in the viewgraph is scaled. Previous investigations with similar ratios of δ/a have revealed that three-dimensional effects due to transverse curvature alter the mean properties of the flow ($U(y)$, C_f , etc.) and that the outer flow and motion of eddies become independent of the wall.

FLOW FACILITY AND MEASUREMENT TECHNIQUES



Fixed Flow Conditions:

- $U_\infty = 11.4$ m/s
- $Re_\theta = 2870$
- $\delta/a = 5.04$

Wall Pressure Measurements:

- Single subminiature electret condenser microphone
- $d = 25.9$, pinhole

Streamwise Velocity Measurements:

- Traversable hot-wire probe
($0 \leq x/\delta \leq 1.5$, $y^+ = 14$ to $y/\delta = 1.9$)
- $l = 18.5$, $l/d = 203$

Viewgraph 4

The flow facility and measurement techniques used for this investigation are shown here. To eliminate boundary layer symmetry problems associated with cylinder sag, a vertical wind tunnel was specifically designed and built for these experiments. The boundary layer pressure-velocity measurements were carried out at a fixed flow speed of 11.4 m/s and a distance of 2.48 m downstream from the leading edge of the cylinder (measurement position is indicated with a circle). These conditions correspond to a Reynolds number, based on momentum thickness, of 2870 and a transverse curvature ratio, δ/a , of 5.04.

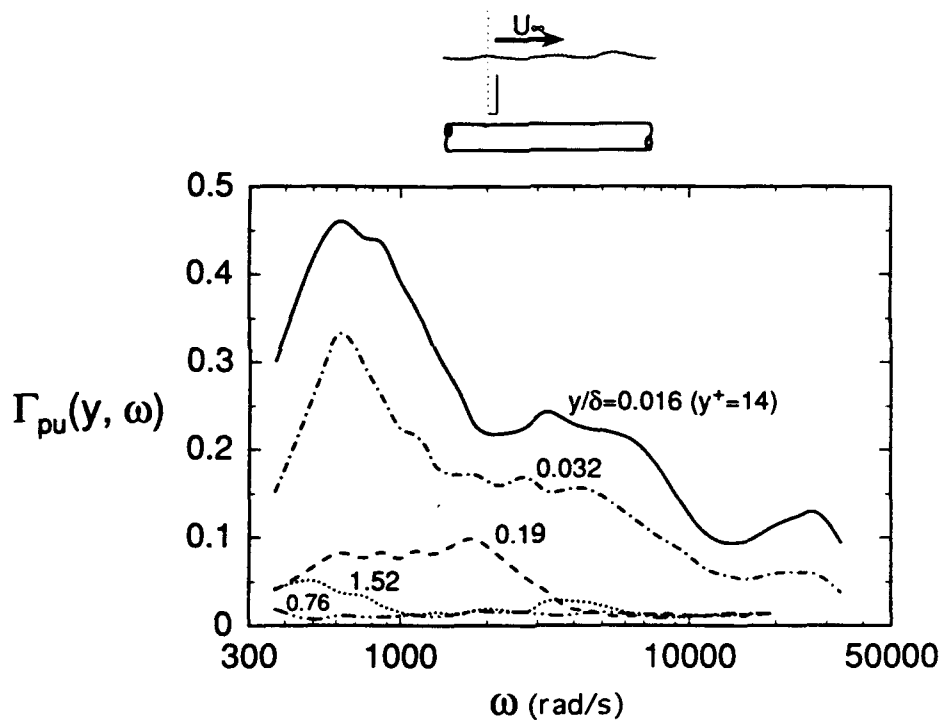
Wall pressure was measured at a single fixed position on the surface of the cylinder with a subminiature electret condenser (or hearing-aid) microphone with a pinhole diameter of 26 viscous lengths (v/u_τ , $u_\tau = (\tau_w/\rho)^{1/2}$). The turbulent streamwise velocity was measured throughout the boundary layer with a traversable hot-wire probe having a wire length of 18.5 viscous lengths and a length-to-diameter ratio of 203. The velocity measurements were performed over the streamwise range $0 \leq x/\delta \leq 1.5$ and wall-normal range $y/\delta = 0.016$ ($y^+ = yu_\tau/\nu = 14$) to $y/\delta = 1.9$. Although measurements were also made in two other circumferential planes ($\theta = 20$ and 40°), only results in the x-y plane containing the microphone ($\theta = 0^\circ$) are presented.

CROSS-SPECTRAL RESULTS

The first results are pressure-velocity cross spectra, which help to establish the spatial extent and character of the turbulent flow structures contributing to the fluctuating wall pressure.

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PRESSURE-VELOCITY COHERENCE FUNCTIONS



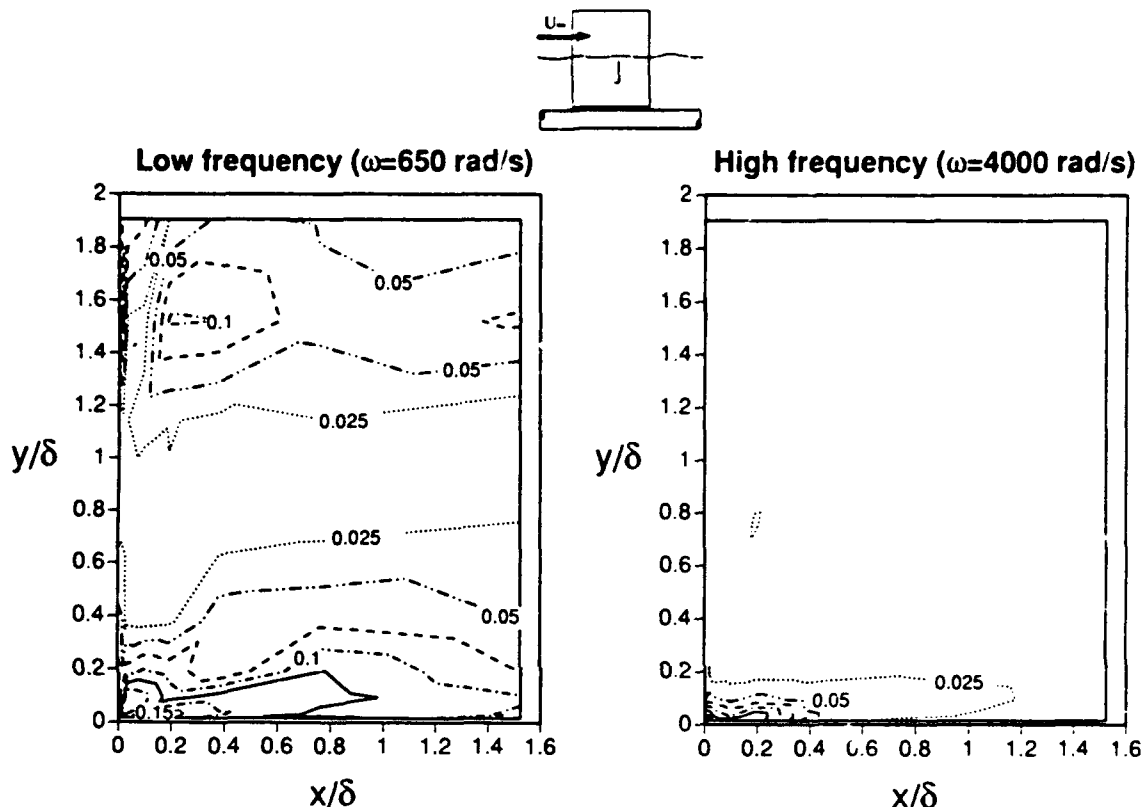
Viewgraph 5

The above viewgraph shows the coherence function or normalized cross-spectral magnitude between the fluctuating wall pressure and the turbulent streamwise velocity at various wall-normal positions of the hot-wire probe immediately above the pressure transducer. At first glance, the coherence functions exhibit an overall decrease in magnitude with increasing distance from the wall, as we would expect since the strength of the contribution of turbulent sources to the wall

pressure is inversely proportional to y . Upon closer examination, however, it can be seen that the low-frequency coherence levels, centered about 650 rad/s, decrease with increasing y only up to $y/\delta = 0.76$, where the coherence is essentially zero. Beyond this point, the coherence levels at this frequency actually increase again, reaching a maximum for the measurement at $y/\delta = 1.52$.

Also visible is a region of elevated coherence levels at high frequencies, centered about 4000 rad/s, for measurements made close to the wall. Although the frequency at which the peak energy occurs decreases with increasing y , this behavior is primarily due to the pressure-transducer/hot-wire separation distance (y) acting as a lowpass filter, allowing only eddies with a scale larger than y to be correlated. In any case, because these near-wall coherence functions contain concentrations of energy at both high and low frequencies, they are bimodal in character, indicating the presence of two distinct flow scales near the wall.

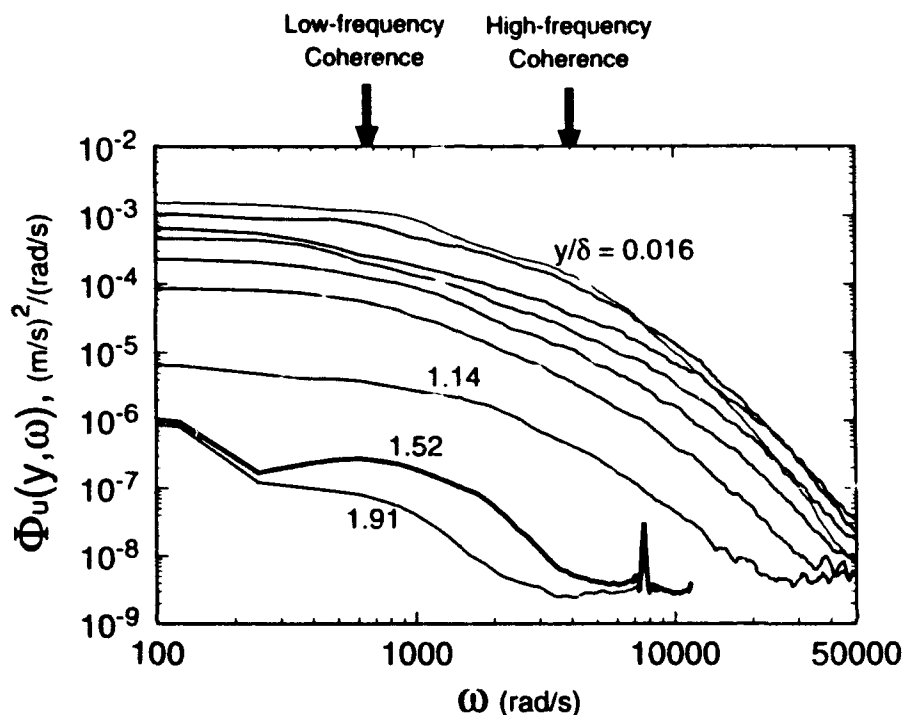
ISOCOHERENCE PRESSURE-VELOCITY CONTOURS



Viewgraph 6

The trends observed immediately above the pressure transducer in the previous viewgraph can actually be seen to exist throughout the entire domain of the measurements, as shown in these isocoherence contour plots. The contours are constructed by plotting the coherence levels at two frequencies, representative of the two frequencies of coherent activity, for all 72 points measured in the x-y plane. At low frequencies (left plot), the elevated coherence levels observed both near the wall and beyond the edge of the boundary layer exist across the entire streamwise extent of the measurements, with a resulting band of very low coherence between them. The high-frequency coherence (right plot) can be seen to be concentrated in the inner region ($y/\delta \leq 0.2$), with a streamwise extent on the order of δ . Because of the overlap in space of the low- and high-frequency coherence near the wall, it seems likely that the two flow disturbances are somehow interrelated or interdependent. The obvious question, however, is, What are the sources of the low- and high-frequency coherence?

STREAMWISE VELOCITY SPECTRA



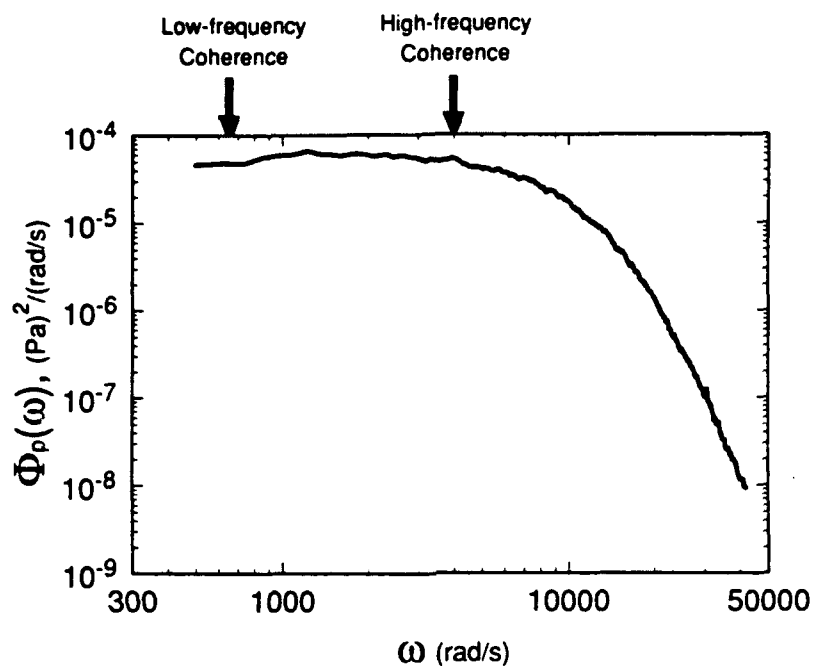
Viewgraph 7

Shown in this viewgraph are the streamwise velocity spectra across the turbulent boundary layer. The spectra within the boundary layer ($y/\delta < 1$) are broadband, typical of turbulence spectra, while those outside of the boundary layer ($y/\delta > 1$) are band limited in character, representative of the organized irrotational motion of the turbulent/potential-flow interface. Because the location of the low-frequency, pressure-velocity coherence, indicated by the left arrow, coincides with the frequency at which the maxima occur in the velocity spectrum outside of the boundary layer, the source of the low-frequency coherence is apparently the outer irrotational motion. Because the low-frequency coherence exists both in the turbulent/potential-flow interface and near the wall, it would appear that the large-scale, outer-flow structures that contribute to the wall pressure extend very close to the wall. Although the flat plate pressure-velocity coherence measurements available (Russell and Farabee, 1991) are nowhere near this extensive, they do not exhibit elevated low-frequency coherence levels near the wall. If this difference is related to

transverse curvature, it would imply that the large-scale structure has a more dominant influence on the overall turbulence dynamics and near-wall flow in the cylindrical boundary layer than in the flat plate boundary layer. However, without more extensive flat plate boundary layer pressure-velocity coherence measurements made closer to the wall, conclusive statements on the effect of transverse curvature on this inner-flow/outer-flow interaction cannot be made.

The source of the high-frequency pressure-velocity coherence, indicated by the second arrow, is not at all apparent from these velocity spectra.

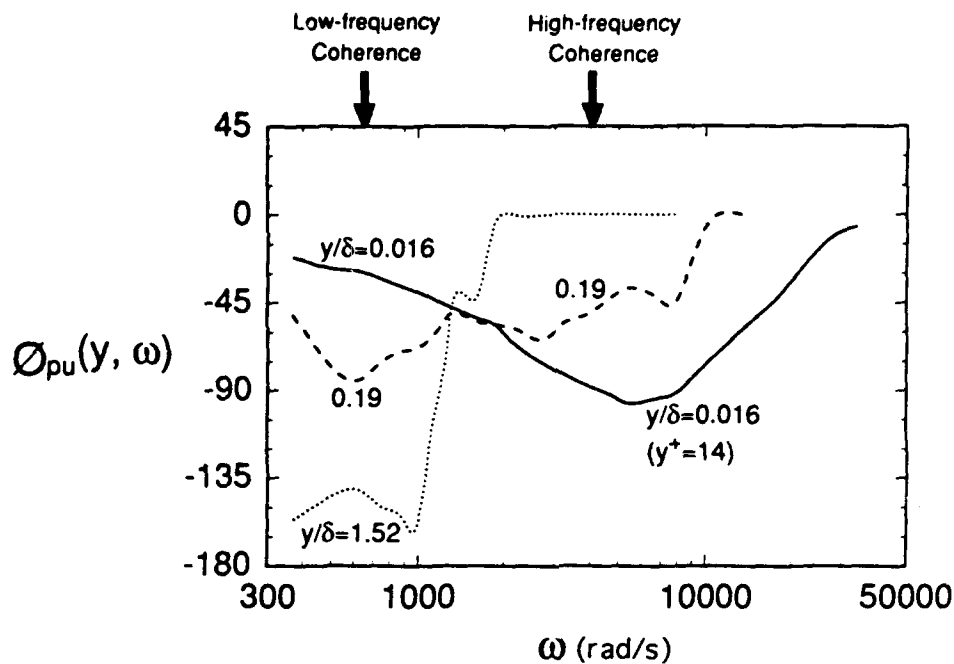
WALL PRESSURE SPECTRUM



Viewgraph 8

Similar to the streamwise velocity spectra, the source of the high-frequency coherence is also not particularly apparent from the wall pressure spectrum, as can be seen in this viewgraph. Although the high-frequency pressure-velocity coherence is not reflected in either the pressure or velocity autospectra, the fact that it exists only in the inner region (viewgraph 6) suggests that the source is a small-scale structure near the wall.

PRESSURE-VELOCITY PHASE FUNCTIONS



Viewgraph 9

Further insight into the character of both the high- and low-frequency disturbances can be obtained by examining the phase of the pressure-velocity cross spectra, as shown in this viewgraph, at three wall-normal positions of the hot-wire probe immediately above the pressure transducer. The cross spectrum is defined so that a negative phase implies that the pressure leads the velocity. At frequencies corresponding to the low-frequency concentration of coherent energy ($\omega \approx 600$ rad/s), a systematic variation in phase with increasing y occurs from roughly -30° at the closest measurement made to the wall to near -180° for the farthest measurements from the wall. This systematic variation in low-frequency phase from the wall to the potential flow appears to confirm the presence of a large-scale outer structure with dynamical significance throughout the entire boundary layer.

At frequencies corresponding to the high-frequency coherent energy ($\omega \approx 4000$ rad/s) measured near the wall ($y^+ = 14$), the phase is -90° . As will be discussed shortly, this phase is

consistent with the relationship between conditionally sampled large-amplitude wall pressure peaks and velocity shear layers in the near-wall region, suggesting that the high-frequency coherent energy may be associated with the turbulence-generating events near the wall.

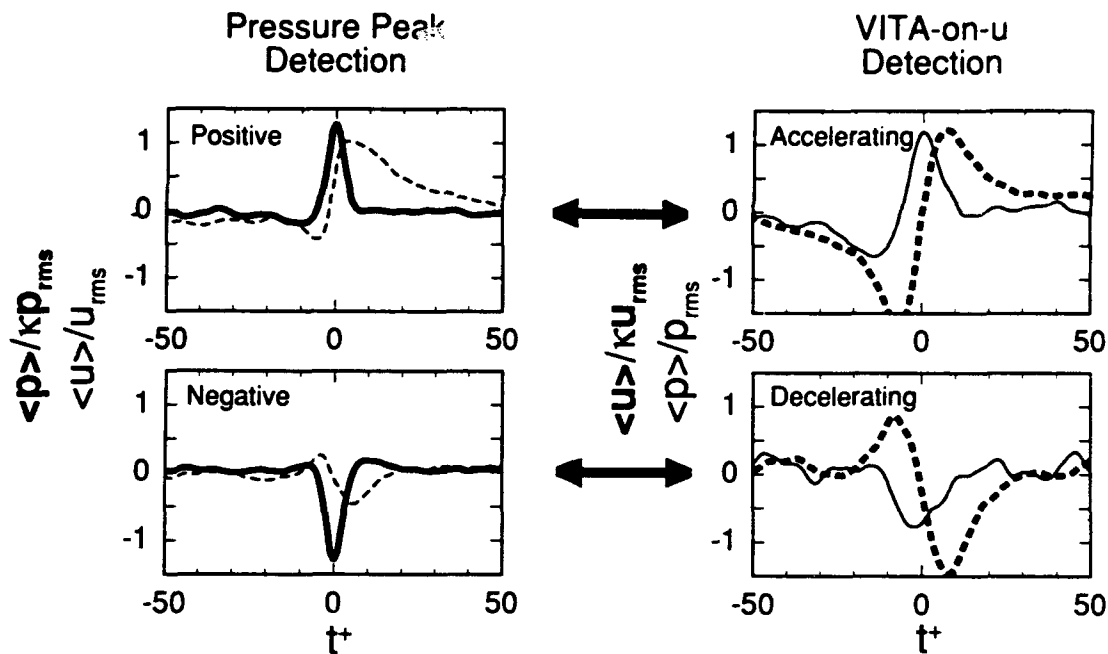
It should be pointed out that although qualitatively similar pressure-velocity phase relationships can be deduced from pressure-velocity correlation measurements performed in flat plate boundary layers, phase results similar to these have not been reported. Consequently, quantitative effects of transverse curvature are difficult to deduce.

CONDITIONALLY SAMPLED RESULTS

To identify the near-wall, high-frequency sources of the wall pressure, conditional sampling techniques have been utilized to examine the relationship between large-amplitude wall pressure fluctuations and high-shear layers in the near-wall region—both of which are believed to be associated with turbulence production near the wall in flat plate boundary layers.

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CONDITIONALLY AVERAGED PRESSURE AND VELOCITY SIGNATURES ($y^+ = 14$)



Viewgraph 10

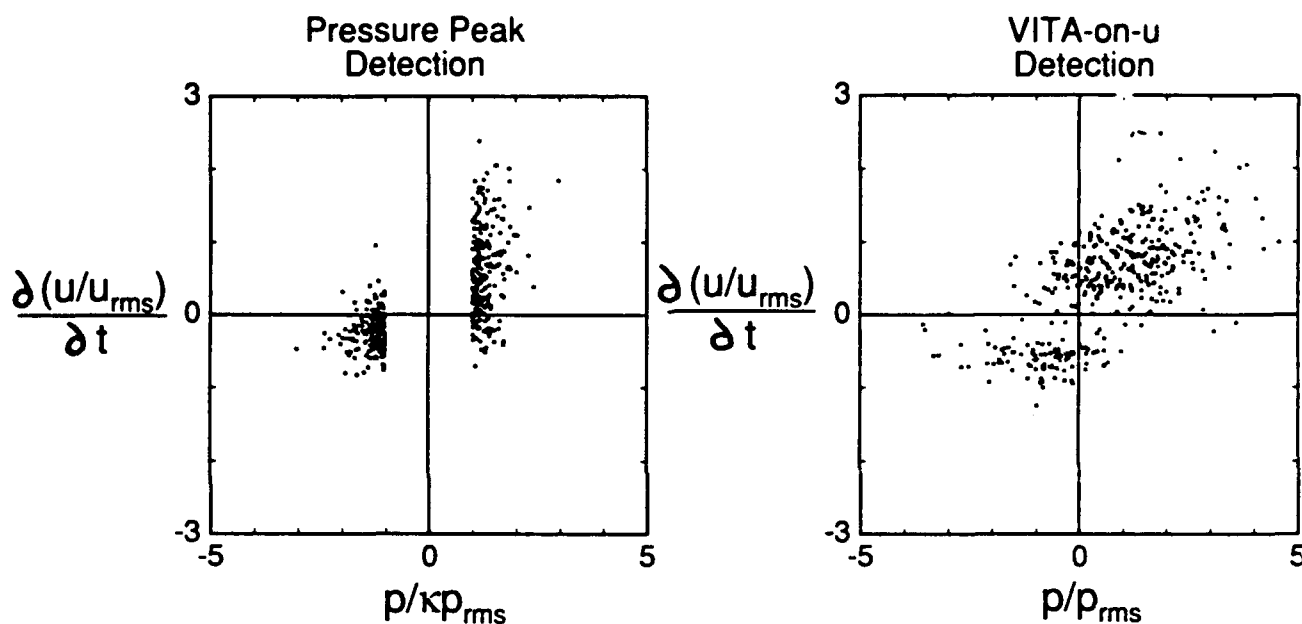
The conditionally averaged pressure and velocity signatures with the hot wire at $y^+ = 14$ are shown in this viewgraph. In the plots at the left, a pressure-peak detection scheme was used to examine what happens to the streamwise velocity u (dashed line) when the wall pressure p (solid

bold line) is "peaking." In the plots on the right, the VITA (Variable-Interval Time Averaging) detection scheme was used to examine what happens to the wall pressure p (solid) when the short-time variance of the streamwise-velocity signal u (dashed bold) is large.

The pressure-peak detection results indicate that positive large-amplitude wall pressure peaks are associated with local increases or accelerations in streamwise velocity, while the VITA-on- u results indicate that detected streamwise velocity accelerations are associated with positive peaks in the wall pressure. Similarly, detected negative, large-amplitude pressure peaks are associated with local decreases in streamwise velocity, while detected VITA decelerations in streamwise velocity are associated with negative peaks in the wall pressure. This qualitative similarity or reciprocity between the VITA and pressure-peak results illustrates that a bidirectional relationship or coupling exists between large-amplitude wall pressure fluctuations and the rate of change of streamwise velocity near the wall. These relationships are illustrated perhaps more clearly in the next viewgraph.

CONDITIONAL SAMPLING **- p and $\partial u / \partial t$ at time of detection -**

$y^+ = 14$



Viewgraph 11

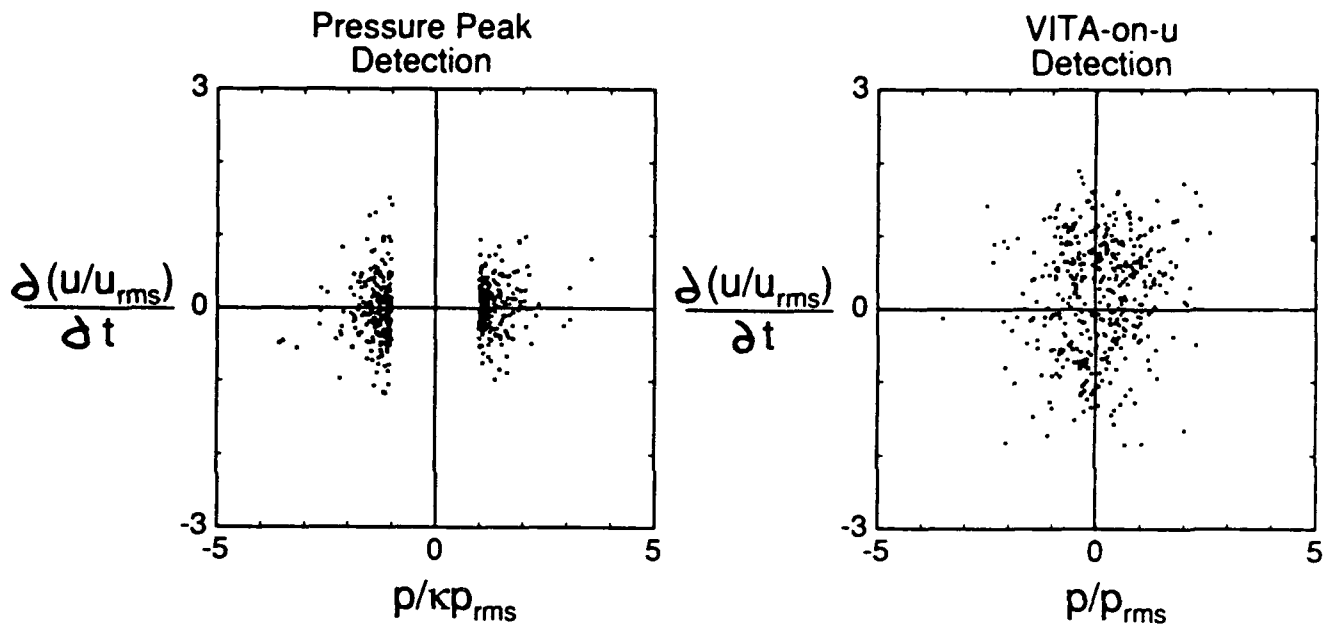
Shown here is a scatter plot of the temporal derivative of u versus the magnitude of p at the time of detection for both detection schemes at $y^+ = 14$. As can be seen, a distinct correlation exists between p and $\partial u / \partial t$ for both detection schemes, as evidenced by the concentration of points along a band through the first and third quadrants. This coupling between p and $\partial u / \partial t$ for both positive and negative peaks indicates that both types of large-amplitude wall pressure fluctuations are directly linked to flow structures in the near-wall region and that both are equally important to the physics of the near-wall flow.

For conditional sampling measurements in flat plate boundary layers, a relationship between pressure peaks and the derivative of u has only been reported for positive pressure peaks.

Negative peaks have instead been weakly associated with the sign of u . Here, no explicit relationship was found between the sign of p and the sign of u , only between the sign of p and the sign of the temporal derivative of u —as found in the cross spectra (viewgraph 9), p and u are simply 90° out of phase. These inconsistencies with the flat plate boundary layer measurements, however, can be somewhat resolved if the large-scale influences in the flat plate conditionally averaged results (Johansson et al., 1987; Haritonidis et al., 1990) are taken into account, suggesting that the observed relationship may be a general feature of all wall-bounded flows.

CONDITIONAL SAMPLING **- p and $\partial u / \partial t$ at time of detection -**

$y^+ = 169$

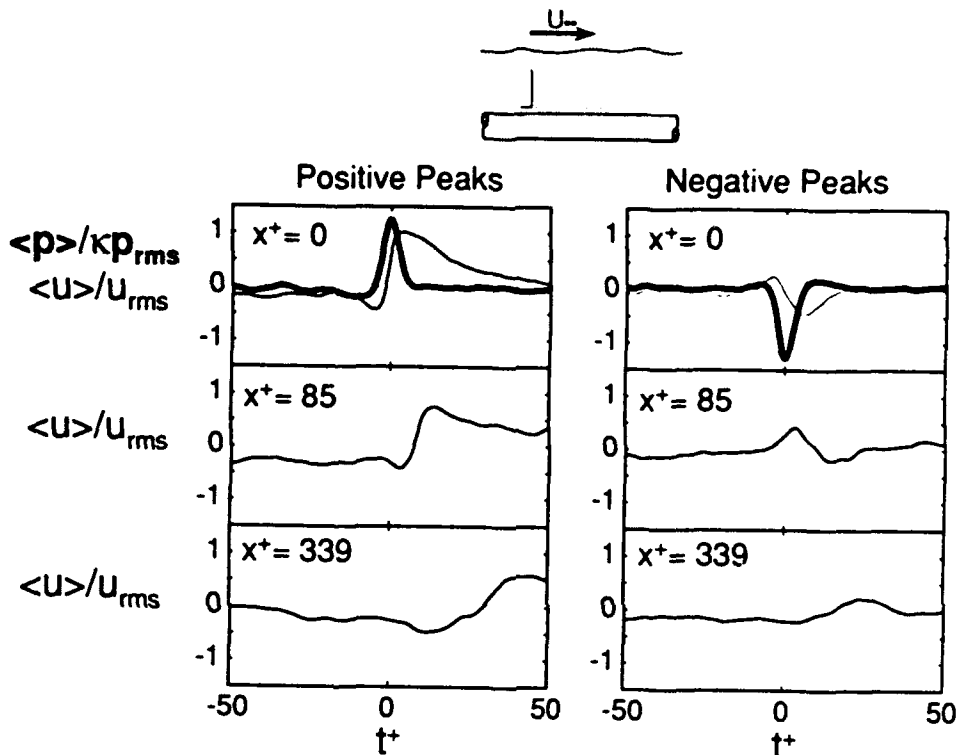


Viewgraph 12

Further insight into the character of the flow structures responsible for the positive and negative pressure peaks can be gained by examining the wall-normal dependence of the coupling between p and $\partial u / \partial t$. This viewgraph, constructed in an identical manner as the last but for the hot wire just outside the near-wall region (i.e., $y^+ = 169$), illustrates that the observed coupling between p and $\partial u / \partial t$ has disappeared rapidly with increased distance from the wall, as evidenced by the random distribution of points in all four quadrants. This disappearance indicates that the flow disturbances responsible for the high-frequency, large-amplitude wall pressure peaks of both positive and negative signs are concentrated within the near-wall region, which is consistent with the character of the turbulence-generating events in a flat plate boundary layer.

Of possibly greater interest, however, are the differences that can be detected between the positive and negative pressure peaks. With increased distance of the hot-wire probe from the wall (in the range $y^+ = 14$ to 169), a more rapid decrease in the coupling between negative pressure peaks and the negative derivative of u occurs than for the positive pressure peaks and the positive derivative of u . Although this is not particularly obvious in this viewgraph, additional differences between the positive and negative pressure peaks can be seen in viewgraph 13.

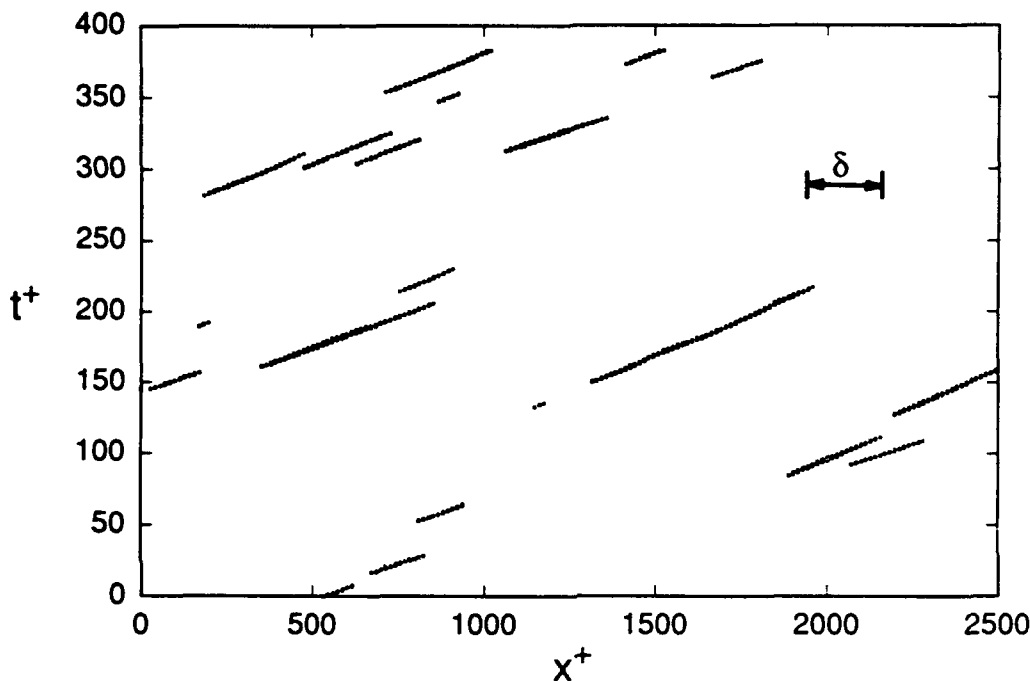
CONVECTIVE BEHAVIOR OF NEAR-WALL STRUCTURES GENERATING LARGE-AMPLITUDE WALL PRESSURE PEAKS



Viewgraph 13

Shown are conditionally averaged velocity and wall pressure signatures with three streamwise separation distances, x^+ , between the pressure transducer and hot-wire probe (at $y^+ = 14$) illustrating the convective behavior of the near-wall flow structures responsible for the positive and negative pressure peaks. When positive-peak to negative-peak results are compared, the flow structures generating the negative peaks have a lower convection velocity (x^+/t^+) and more rapid streamwise decay than the structures generating the positive peaks. These differences suggest that the near-wall turbulent sources that generate the negative wall pressure peaks may be concentrated closer to the wall than those that generate the positive pressure peaks. Whether this is an effect of transverse curvature or a feature of all wall-bounded flows, however, cannot be resolved without more extensive measurements closer to the wall. If it is universal, however, it might explain why negative peaks have appeared less coupled in previous flat plate boundary layer investigations.

SPACE-TIME PROPERTIES OF LARGE-AMPLITUDE (POSITIVE) WALL PRESSURE PEAKS Numerical Data Base ($\delta/a=5$)



Viewgraph 14

The final results, presented in viewgraph 14, are from a preliminary analysis into the space-time properties of the large-amplitude wall pressure fluctuations. This viewgraph, obtained from a data base generated by direct numerical simulation (DNS) of a turbulent boundary layer on a cylinder in axial flow with $\delta/a = 5$ (Neves et al., 1991), is a scatter plot illustrating the space-time trajectories of conditionally sampled *positive* large-amplitude wall pressure fluctuations. Because of the long trajectories for the large-amplitude pressure peaks, it is clear that the near-wall convecting flow structures responsible maintain their identity for very long distances. With these coherent convection distances being on the order of 0.5 to 3δ , a range consistent with the *measured* conditionally sampled results (Snarski, 1992), it seems likely that the large-amplitude pressure fluctuations are coupled to large-scale outer motions. By extending this space-time analysis to include both positive and negative pressure peaks as well as the near-wall velocity fields for the available DNS data bases for cylindrical ($\delta/a = 5, 11$) and planar (channel, flat plate) boundary layers, it is hoped that some of the questions generated during this study can be answered.

CONCLUSIONS

Investigation: examine relationship between fluctuating wall pressure and turbulent flow structures in boundary layer with transverse curvature

- Two primary groups of flow disturbances contribute to fluctuating wall pressure
- Both (+) and (-) large-amplitude wall pressure peaks generated by convecting near-wall flow structures that maintain identity for long distances ($0.5 - 3 \delta$)
- Sources of (-) wall pressure peaks located closer to wall than sources for (+) peaks

Objective: understand how transverse wall curvature influences fluctuating wall pressure and turbulence structure that exists in an equilibrium flat plate boundary layer

- Low- ω and high- ω disturbances interdependent \Rightarrow enhanced inner/outer interaction ?
- Other ?

More complete understanding of the effect of transverse wall curvature will require:

- Complete set of p-u measurements in flat plate and transverse curvature TBL's
- Analysis of existing flat plate and transverse curvature ($\delta/a = 5$ & 11) TBL data bases

Viewgraph 15

This investigation has examined the relationship between the fluctuating wall pressure and the turbulent flow structures in a boundary layer with transverse wall curvature and has resulted in several interesting findings concerning a turbulent boundary layer on a cylinder in axial flow. First, two primary groups of flow disturbances were identified that contribute to the wall pressure: (1) low-frequency, large-scale structures with dynamical significance throughout the boundary layer and (2) high-frequency, small-scale structures concentrated close to the wall, presumably associated with the large-amplitude pressure fluctuations. Second, both positive *and* negative large-amplitude (high-frequency) pressure fluctuations were found to be generated by convecting near-wall flow structures that maintain their identity for long distances. Third, the flow structures responsible for the negative pressure peaks may be located closer to the wall than the sources for the positive pressure peaks.

The objective of this research has been to understand how transverse wall curvature influences the fluctuating wall pressure and turbulence structure that exist in an equilibrium flat plate boundary layer. The bimodal coherence functions near the wall and long convective lengths for the high-frequency, large-amplitude wall pressure fluctuations tend to indicate that the low- and high-frequency disturbances in the boundary layer with transverse curvature are interdependent. Even so, it is difficult to conclude whether or not transverse curvature acts to enhance the outer-flow/inner-flow interaction over the flat plate boundary layer case because (1) there are insufficient flat plate boundary layer results available for comparison and (2) the dynamics and interaction of structures in flat plate boundary layers are not yet fully understood. As a result, the exact influence of transverse curvature on this, as well as on the other flow features observed, remains inconclusive. Consequently, a better understanding of the effect of transverse curvature will require either a more complete set, or complementary sets, of pressure-velocity measurements in flat plate and transverse curvature turbulent boundary layers, or a more extensive analysis of the existing DNS data bases for flat plate and transverse curvature turbulent boundary layers.

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